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Investigation on effectiveness of a prefabricated vertical drain during cyclic loading

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Abstract. The effectiveness of prefabricated vertical drains (PVDs) in enhancing the stability of soft soils during cyclic loading was investigated using triaxial cyclic loading tests. Both undrained and with PVD tests were employed to study the associated excess pore pressure and accumulated strain under the repeated loading condition. The loading frequency and cyclic stress ratio have been chosen to be the variables which influence the performance of soft clays. The experimental results illustrate that with PVDs, the excess pore water pressure generation during cyclic loading decreases significantly. It is found that the excess pore water pressure build up depends on both loading frequency and cyclic stress ratio. The excess pore water pressure will increase when each of them is increased. Furthermore, when the loading frequency is 0.1 Hz, the ratio of coefficient of consolidation under cyclic loading to that under static loading is almost one. With the increasing loading frequency, this ratio increases accordingly.

1. Introduction

Settlement and shear strength problems for cohesive soils under cyclic loading emerge from the construction of railways founded on soft clays. The constraints of tight construction schedules, restricted space, safety and environmental issues have continued to demand unfailing innovation in the design and construction. In this context, prefabricated vertical drains (PVDs) have been used to speed up the dissipation of excess pore water pressure thereby increasing the soil stability [1, 2, 4]. This study further examines the important role of prefabricated vertical drains installed in soft clays, by preventing the accumulation of excess pore water pressure during cyclic load application to critical values. Series of undrained and with PVD cyclic loading tests with different frequencies and cyclic stress ratios were carried out. The outcomes of this study will be most beneficial for improving the stability of rail tracks constructed on estuarine soils with low bearing capacity and high compressibility.

2. Apparatus and testing procedure

2.1. Testing apparatus and specimen preparation

A large scale cylindrical triaxial equipment (Figure 1), which is designed and built at the University of Wollongong [3] is used to conduct the tests. The details of this equipment are demonstrated by Indraratna et al. [4]. The clay employed in this study was kaolinite. The basic physical properties of the soil are listed in Table 1. The detailed descriptions of clay mixture, sample placement, pore water pressure transducer position and prefabricated vertical drain installation were also explained elsewhere by Indraratna et al. [4].

Table 1. Basic properties of kaolinite used in the tests.

Specific gravity	Liquid limit	Plastic limit	Compression index	Swelling index
G_s	w_L	w_p	C_c	C_s
2.7	55	27	0.42	0.06

Table 2. Specimen conditions of cyclic loading tests.

Test number	σ'_{10} /kPa	σ'_{30} /kPa	Frequency /Hz	CSR
U05 ^a	40	24	5	0.39
U10 ^a	40	24	10	0.27
D02 ^a	40	24	2	0.41
D05 ^a	40	24	5	0.49
D10 ^a	40	24	10	0.37

^a U indicates undrained test while D indicates partially drained with PVD test. The number following U or D indicates the loading frequency.

2.2. Cyclic loading test procedure

Both undrained and with PVD cyclic loading tests were conducted to investigate the behaviour of PVDs during cyclic loads. For the tests with PVD, only central drainage via PVD was permitted. A range of loading frequencies from 2 to 10 Hz was used to examine its effect on cyclic performance. A series of cyclic stress ratios (CSR) varies from 0.27 to 0.49, where $CSR = q_{cyc} / p'_{c0}$. q_{cyc} is the cyclic deviator stress and $p'_{c0} = (\sigma'_{10} + 2\sigma'_{30}) / 3$. The undrained and with PVD cyclic loading test conditions are summarized in Table 2. During the tests, four excess pore water pressure transducers were used to record the data. They are at different heights and with different radial distances to the PVD. Figure 2 shows the location of the pore pressure transducers.



Figure 1. The large scale triaxial cell.

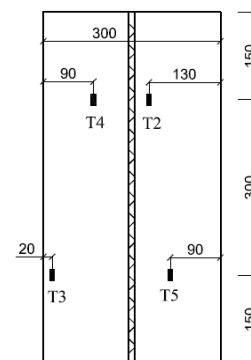


Figure 2. Sample size and locations of the transducers (all units are in millimeters).

3. Test results and analysis

3.1. Excess pore water pressure generation during undrained tests

Figure 3 shows the relationship between the normalized excess pore water pressure and normalized number of cycles in undrained tests. u_r is the excess pore water pressure at minimum deviator stresses (Figure 4) corresponding to the loading cycles N and u_{3000} is the residual excess pore water pressure at the end of 3000 cycles where both the stresses and strains remain almost constant [4]. The excess pore water pressure build up trends are similar for both tests conducted under 5Hz and 10Hz. The excess pore water pressures reach 80% of the final value within 500 to 600 cycles and then increases slightly afterwards, which is similar to the observation of Sakai et al. [5]. The relationship between the normalized excess pore water pressure and the number of cycles can be expressed by:

$$\begin{cases} u_r / u_{600} = (4 / \pi) \operatorname{tg}^{-1} \left[(N / 600)^{1/\alpha_1} \right], 0 \leq N \leq 600 \\ u_r / u_{3000} = (4 / \pi) \operatorname{tg}^{-1} \left[(N / 3000)^{1/\alpha_2} \right], 600 \leq N \leq 3000 \end{cases} \quad (1)$$

Figure 5 shows the final residual excess pore water pressure ratios ($u^* = u_{3000} / p'_{c0}$) for both undrained 5Hz and undrained 10Hz. $z/h = 0$ and $z/h = -1$ represent the top of the specimen and the bottom of the specimen, respectively. It is obvious the greater the loading frequency, the higher the excess pore water pressure generation. The excess pore water pressure under 10Hz is approximately 2 times that under 5Hz. The excess pore water pressure tends to decrease from the top to the bottom which might be due to the attenuation of energy transferred through the specimen.

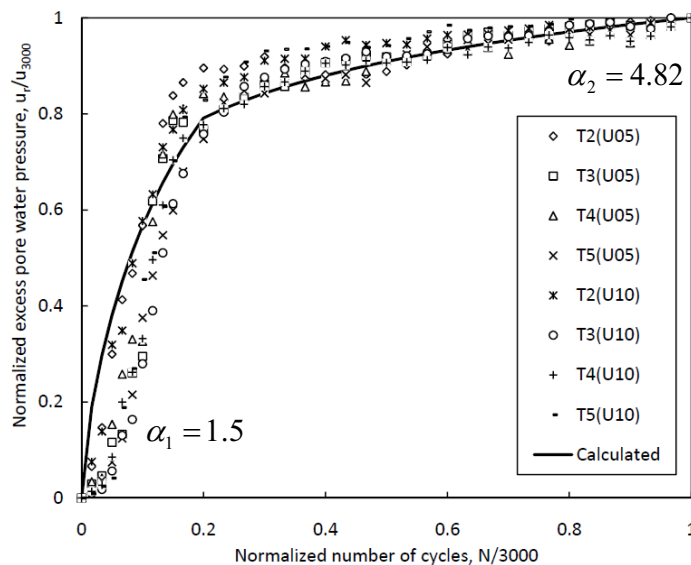


Figure 3. The relationship between the normalized excess pore water pressure and normalized number of cycles.

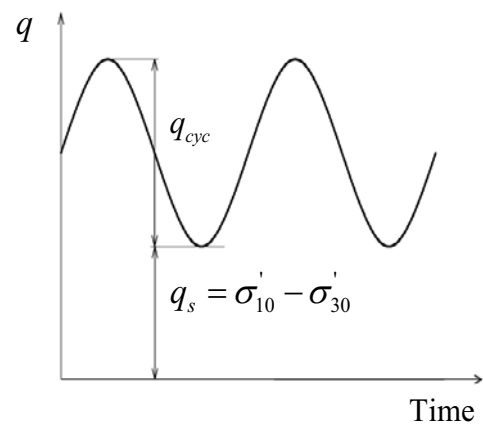


Figure 4. Cyclic stress applied to the soil sample.

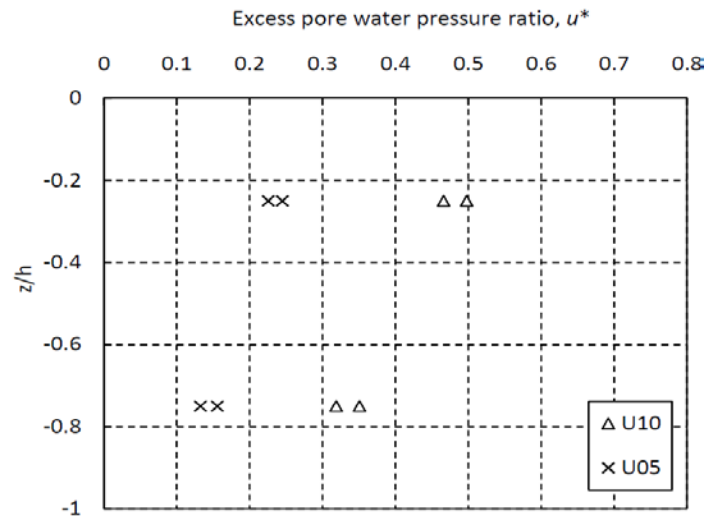
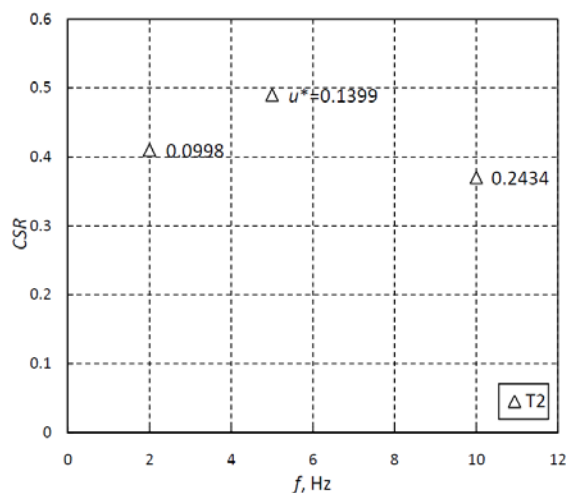


Figure 5. Final excess pore water pressures with depth during undrained cyclic loading.

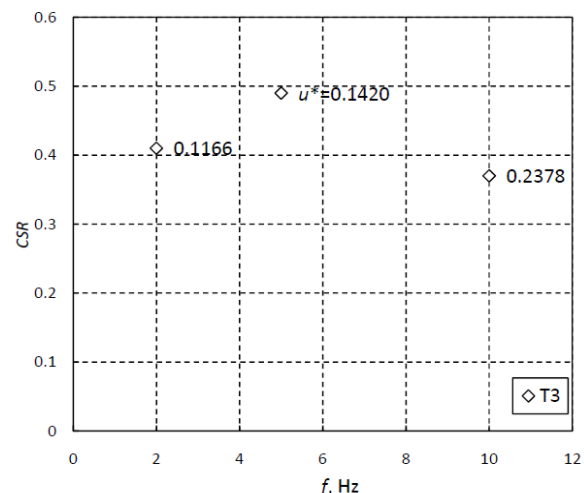
3.2. Excess pore water pressure generation in partially drained tests

Figure 6 shows the value of maximum excess pore water pressure ratio with different cyclic stress ratio (CSR) and loading frequency (f) at different locations. It is known that the excess pore water pressure increases with the increasing frequency and CSR . So the maximum excess pore water pressure ratio depends on the combination of frequency and CSR . The transducers at different locations have the u^* values of similar tendency. When both the loading frequency and CSR of test D05 are greater than those of test D02, the u^* of test D05 is higher than that of test D02. However, the u^* from D10 is the highest when its CSR is lower and loading frequency is higher.

With the results of undrained tests and tests with PVD (Figure 7), the ratio between excess pore water pressure obtained from the test with PVD to undrained excess pore water pressure (R) can be determined at different locations. The effect of the PVD to prevent the excess pore water pressure to build up is significant, as all the values of R are smaller than unit. Furthermore, the dissipation of excess pore water pressure is more obvious at the locations close to the PVD. When the drainage path is only 0.13 of the total drainage path, the excess pore water pressure ratio is reduced significantly from 1.0 to approximately 0.4 to 0.5. When the drainage paths become larger (i.e. $x/r = 0.4$ and 0.86), the excess pore water pressure can reduce to 0.6 to 0.8.



(a)



(b)

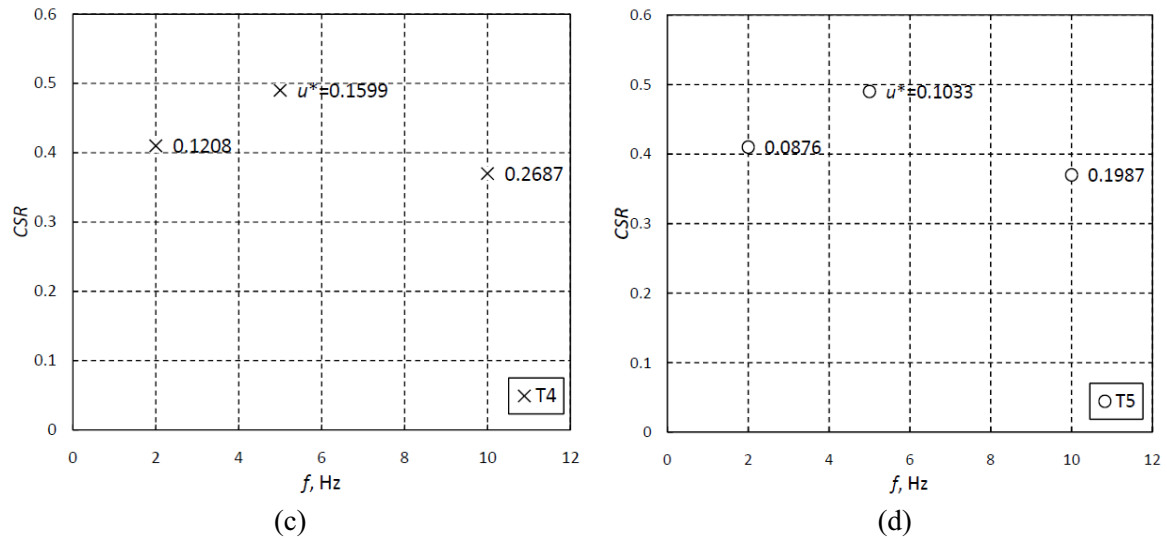


Figure 6. The excess pore water pressure ratios with CSR and f (D02, D05 and D10).

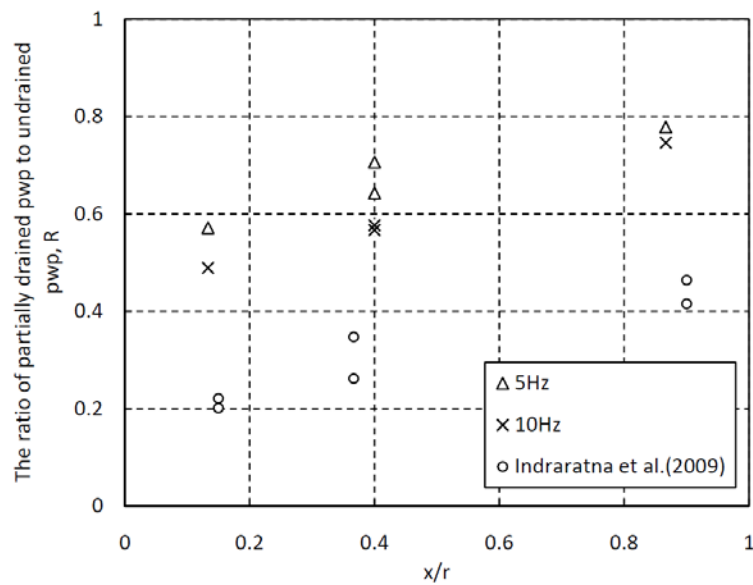


Figure 7. The effectiveness of the drainage during cyclic loading (r = the radius of the specimen and x = the radial distance from the prefabricated vertical drain).

3.3. Development of shear strains

The relationship between shear strains and excess pore water pressures is shown in Figure 8. With the same shear strain, the excess pore water pressures of undrained tests are greater than those with PVDs, which implies that PVDs effectively improve the stability of soft clays.

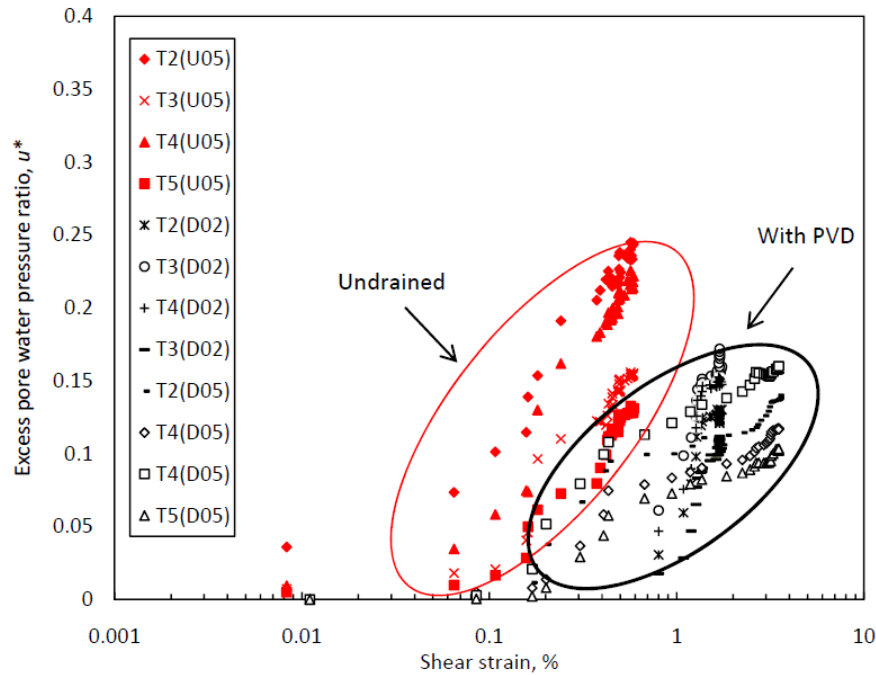


Figure 8. Relationship between the accumulated shear strains and the generated excess pore water pressures during cyclic loading with and without PVD

4. Modelling of excess pore water pressure generation under cyclic loading condition with PVD

4.1. Excess pore water pressure generation model

Under the cyclic loading condition, the generation and dissipation of the excess pore water pressure due to PVD occur simultaneously. Hyodo and Yasuhara [6] proposed a procedure for evaluating the performance of soil under partially drained cyclic loading conditions. The excess pore water pressure at radius (r) and depth (z) at time (t) can be expressed by Eq. (2) for the unit cell with radial drainage:

$$\frac{1}{c_h} \left(\frac{\partial^2 u(r, z, t)}{\partial r^2} + \frac{1}{r} \frac{\partial u(r, z, t)}{\partial r} \right) = \frac{\partial u}{\partial t} + \frac{\partial u_r}{\partial t} \quad (2)$$

Where, $\frac{1}{c_h}$ is the coefficient of consolidation for radial flow under cyclic loading conditions,

$u(r, z, t)$ is the excess pore water pressure at radius r and depth z at time t . $\frac{\partial u_r}{\partial t}$ is the rate of internal

excess pore water pressure generation during undrained cyclic loading. The above formulation can be used to predict the excess pore pressure during the cyclic loading.

4.2. Implicit finite difference method

In this paper, implicit finite difference method is adopted to simulate the excess pore water pressure response under cyclic loads. Under cyclic loading condition with PVDs, The excess pore pressure at time ($t+\Delta t$) can be given by:

$$u^n(t + \Delta t) = \frac{1 - \lambda_h}{1 + \lambda_h} u^n(t) + \frac{\lambda_h}{2(1 + \lambda_h)} \left[\left(1 - \frac{1}{2i} \right) (u^{n-1}(t) + u^{n-1}(t + \Delta t)) + \left(1 + \frac{1}{2i} \right) (u^{n+1}(t) + u^{n+1}(t + \Delta t)) \right] + \frac{1}{1 + \lambda_h} (u_r(t + \Delta t) - u_r(t)) \quad (3)$$

where, $\lambda_h = \frac{c_h \Delta t}{\Delta r^2}$ and $(u_r(t + \Delta t) - u_r(t))$ represents the internal excess pore water pressure generation subjected to undrained cyclic loading during time interval Δt , which can be expressed as:

$$u_r(t + \Delta t) - u_r(t) = \frac{\partial u_r}{\partial t} \Delta t = \left(\frac{\partial u_r}{\partial N} \right) \left(\frac{dN}{dt} \right) \Delta t \quad (4)$$

4.3. Comparison between measured and calculated excess pore water pressures

Based on the undrained curves of 5Hz and 10Hz and Equation 1, the values of α are 1.5 and 4.82 respectively (Figure 3). It is assumed in this paper, that the excess pore water pressures in undrained tests are distributed linearly with the maximum value at the top of sample and the minimum value at the bottom of sample. \bar{c}_h can be back-calculated based on Equation 2 (Figure 9). Figure 10 illustrates the relationship between \bar{c}_h / c_h and loading frequency. c_h is the coefficient of consolidation under static loading condition. When the loading frequency is 0.1 Hz, \bar{c}_h / c_h is almost one. The loading frequency increases the value of \bar{c}_h / c_h .

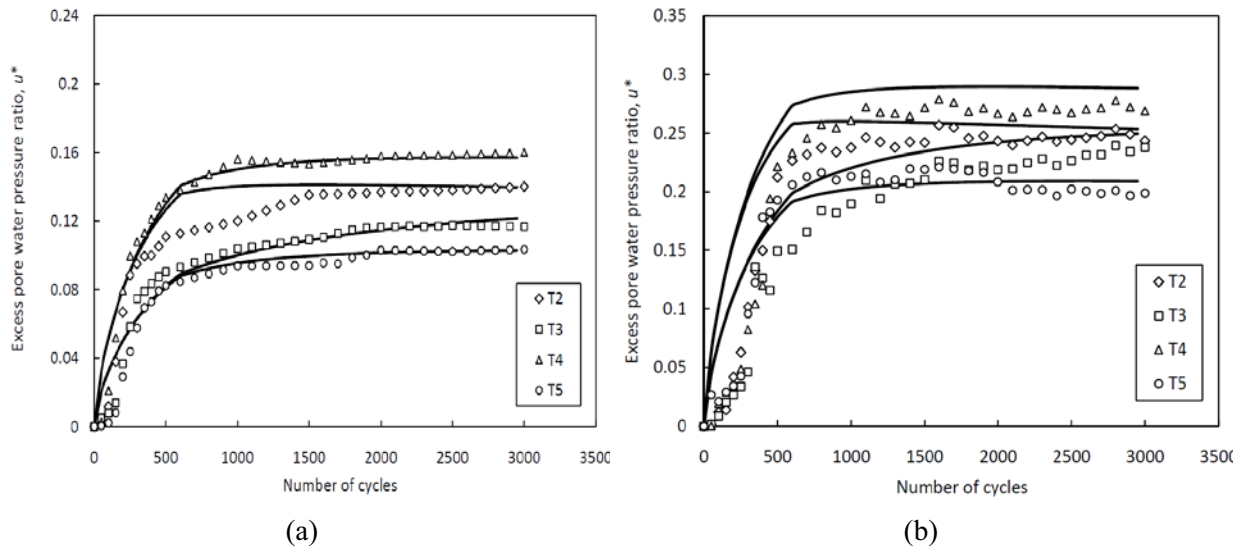


Figure 9. (a) The comparison of the predicted value with tested value (D05); (b) The comparison of the predicted value with tested value (D10).

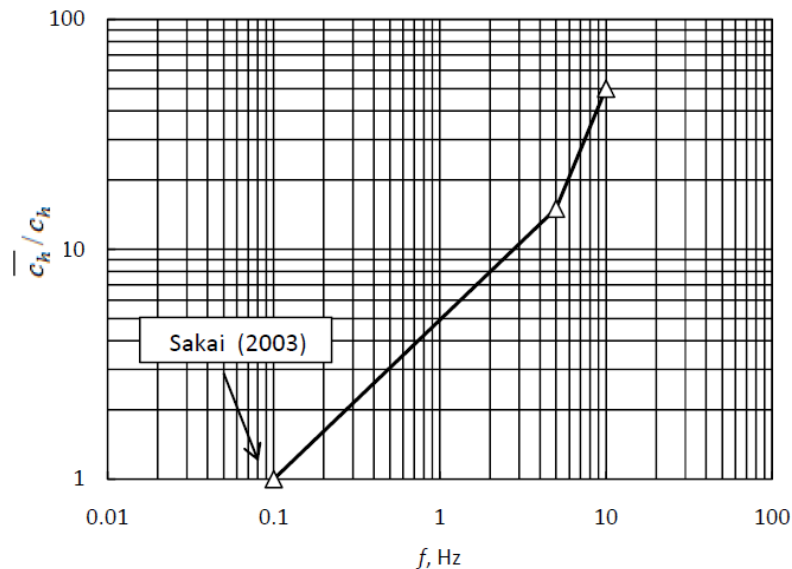


Figure 10. The relationship between \bar{c}_h / c_h and f .

5. Conclusion

Prefabricated vertical drain is an effective method to dissipate excess pore water pressure during cyclic loads. The test series were carried out using large-scale triaxial process simulation apparatus to investigate the effectiveness of PVD under cyclic load condition. The generation and dissipation of excess pore water pressure depends on the cyclic stress ratio and loading frequency. With PVDs, the residual excess pore water pressure reduces significantly, which implies that the soil improved by PVDs can resist a higher cyclic stress without initiating failure. PVD can reduce the accumulation of excess pore pressure by 50%-80% depending on the location, applied frequency and cyclic stress ratio. The numerical solution to predict the excess pore water pressure during cyclic loading with PVD is proposed considering the effect of frequency. It is found that the coefficient of consolidation for radial flow under cyclic loading condition increases with the increasing frequency.

Reference

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